

# Utilization of Multi-Mission Satellite Altimetry for Wave Energy with Site Suitability Analysis using the Analytic Hierarchy Process

**Mat Nizam Uti**

Geospatial Imaging and Information Research Group, Faculty of Built Environment and Surveying, Universiti Teknologi Malaysia, Malaysia  
mnizam65@graduate.utm.my

**Ami Hassan Md Din**

Geospatial Imaging and Information Research Group, Faculty of Built Environment and Surveying, Universiti Teknologi Malaysia, Malaysia  
amihassan@utm.my (corresponding author)

**Norhakim Yusof**

Geoinformation Department, Faculty of Built Environment and Surveying, Universiti Teknologi Malaysia, Malaysia  
norhakim@utm.my

**Syarif Abdul Asaad Jairin**

Geospatial Imaging and Information Research Group, Faculty of Built Environment and Surveying, Universiti Teknologi Malaysia, Malaysia  
saasaad2@graduate.utm.my

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## ABSTRACT

Space technology advancements have enabled the acquisition of marine data that support the research on wave energy as an alternative to reduce fossil fuel dependency and mitigate climate change. Malaysia's ocean renewable energy potential lacks attention from local authorities due to insufficient in-situ data, posing challenges in investigating ocean characteristics, such as wave heights. This study investigated Malaysia's wave energy potential using extensive significant wave height data from multiple altimetry missions. The former assessed site suitability using the Analytical Hierarchy Process (AHP) multicriteria analysis, incorporating marine constraints, namely socioeconomic, physical, and environmental factors. The multicriteria findings were integrated into a Geographical Information System (GIS) to improve the site suitability analysis and generate a localized suitability index for wave energy. Validation of satellite altimeter data with in-situ measurements showed a strong correlation and low RMSE. AHP analysis indicated good consistency in the criteria analysis, with a consistency ratio of 0.045, which falls below the limit of 0.1. The coastal and offshore regions of the Malaysian seas are suitable for harnessing wave energy with energy ranges up to 4.21 kW/m. Therefore, this study provides valuable information to stakeholders and the government to increase their interest in wave energy.

*Keywords-analytic hierarchy process; satellite altimeter; wave energy; multi-criteria*

## I. INTRODUCTION

Changes in the global socioeconomic environment, the environment, natural sources, and social life have increased the demand for renewable energy, particularly for electric generation. Natural sources of electricity generation in Malaysia are believed to experience a shortage in the future due

to environmental impacts and population growth [1-2]. There are various types of ocean energy, including tidal barrage, tidal stream, wave energy, salinity gradient, and ocean thermal energy [3]. The feasibility study of renewable energy requires ocean information and large spatial and temporal resolution to characterize ocean conditions. Coarse spatial information is not ideal for describing spatial variations in sea conditions [4]. To

date, the available information on ocean characteristics in Malaysian waters is based on observations from oil platforms, ships, and buoys [5]. According to [4], satellite measurements have offered large spatial and temporal data to characterize the ocean surface. This study used satellite altimeter data from various altimetry missions to retrieve Significant Wave Height (SWH) data. Although renewable ocean energy could help minimize carbon emissions, there is still concern about the impact of its development on marine space. For example, noise generated during the installation can affect marine life, as its habitat is disturbed, and turbines can block the movement of marine life or even reduce its population [6-7]. This study performs a multicriteria analysis considering environmental, physical, and socioeconomic factors to avoid conflicts, e.g., human activities, marine environment, conservation areas, ship routes, etc. so that the proposed sites for wave energy evade the conflicting areas.

II. DATA AND METHODS

Figure 1 shows the study area, which is circumscribed by latitude from 0° to 14° and longitude from 95° to 120°. The analysis of available resources and site suitability is performed inside the Malaysian Exclusive Economic Zone (EEZ). According to UNGA, the EEZ extends to 200 nautical miles from the territorial baseline and stretches to 12 nautical miles of territorial sea [8] Within this area, the coastal nation has exclusive control and exploitation rights over natural resources. This study used various altimetry missions to retrieve SWH data over the Malaysian seas. The coverage period of the multi-mission satellite altimeter data employed was from January 1993 to December 2020 (28 years). The altimetry mission included ERS-1, TOPEX, Poseidon, ERS-2, Jason-1, Envisat1, Jason-2, Cyrosat-2, SARAL, Jason-3 and Sentinel-3A. Buoy measurements are crucial to assess the accuracy and reliability of other techniques through the validation process. Table I summarizes the buoys engaged in this study.

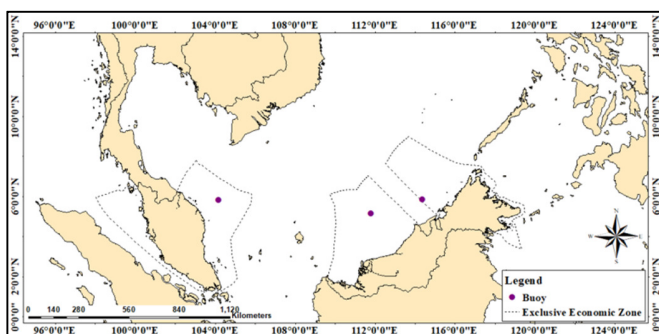


Fig. 1. The study area.

TABLE I. SELECTED BUOY DATA USED IN THIS STUDY

Buoy	Location	Period
Sabah	5.83 N 114.39 E	Nov 04-Dec 07
Sarawak	5.15 N 111.82 E	Jan 09-Jan 12

Validation plays a crucial role in proving the accuracy of the altimetric data. The relationship between the altimeter-

derived and the in-situ data translated into correlation coefficient  $r$  utilizing Pearson's coefficient [9]:

$$r = \frac{\sum_{i=1}^n (x_i - \bar{x}) - (y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^n (y_i - \bar{y})^2}} \tag{1}$$

where  $r$  is the correlation coefficient,  $x_i$  refer to in-situ data,  $\bar{x}$  is the mean value for measured data (in-situ),  $y_i$  is satellite altimeter data, and  $\bar{y}$  is the mean value for the observed data (satellite altimeter). RMSE determines how to fit the data around the line of the best fit. Some studies have shown that satellite altimeters are well correlated, have good RMSE values with in-situ data, and are applicable for energy studies [5,10-11].

The energy density derivation is part of the theoretical resource assessment. The energy density, called the potential energy of the wave energy, is calculated applying an existing equation. Wave energy flow is generally described as the average energy per meter of crest length of wave in kW/m. The exploitation of wave energy resources using Wave Energy Converters (WECs) requires the significant wave height  $H_s$  and wave period  $T_z$  as inputs. The wave energy density can be obtained utilizing (2).  $P_{wave}$  is the wave energy density (kW/m) parameterized in terms of  $H_s$  and  $T_z$ , expressed in meters and seconds, respectively.

$$P_{wave} = 0.49 H_s^2 T_z \tag{2}$$

According to [12], a satellite altimeter is unable to provide a direct measurement for the wave period  $T_z$ . This study applies the indirect estimation of wave period using the Fara-U algorithm (3). This algorithm is developed in the form of significant wave height and wind speed data from a satellite altimeter, employing the symbolic regression method to develop wave period data, and is suitable for the Malaysian sea [12].

$$T_z = 1.299a - 1.127 \tag{3}$$

$$a = 2.247 + \frac{4.947 + 25.399 H_s}{7.562 + H_s + U}$$

where the wave period is denoted as  $T_z$  (s),  $H_s$  is the significant wave height (m), and  $U$  is the wind speed (m/s).

Practical wave energy resource assessment considered the marine constraints as defined in [13-14]. The importance of this analysis is to identify a suitable location by avoiding existing conflicts. There are various applications related to site suitability analysis, such as flood shelter mitigation [15], agricultural management [16], landfill management [17], and coastal management and planning [18]. The selection of a suitable site for ocean renewable energy requires an understanding of the spatial distribution of the marine environment, human activities, and physical criteria in the marine space. However, marine data in Malaysia are difficult to access because there are no centralized and strategically developed marine data centers for marine applications due to a lack of cooperation within and among organizations [19]. This study involves the physical, environmental, and socioeconomic factors, which are represented by several types of data, as presented in Table II.

TABLE II. FACTORS AND SUB-FACTORS USED IN THE SITE SUITABILITY ANALYSIS

Factors	Sub-factors
Environmental	Marine protected areas
	National marine parks
	Coral reefs
	Sea turtle nesting
Physical	Underwater pipelines
	Submarine cables
	Shipping lanes
	Fish main landing point
	Oil and gas areas
	Ports
	Shoreline

The AHP technique comprises certain steps to create a model by breaking down complex problems into smaller, more manageable parts. These steps are the following: (1) Structure the problem hierarchy and create the decision hierarchy, (2) define criteria and create pairwise comparison matrices, (3) create matrices for alternatives based on objectives, (4) verify judgment consistency by calculating the ratio, and (5) calculate weighted average ratings for decision alternatives by selecting the highest-scoring one [20, 23]. Comparisons or adjustments between two elements in AHP can be made using the relative scale between two alternatives [21]. The pairwise comparison is performed using a square matrix, as in (4) [22].

$$A = \begin{pmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{pmatrix} = \begin{pmatrix} \frac{w_1}{w_1} & \frac{w_1}{w_2} & \dots & \frac{w_1}{w_n} \\ \frac{w_2}{w_1} & \frac{w_2}{w_2} & \dots & \frac{w_2}{w_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & \dots & \frac{w_n}{w_n} \end{pmatrix} = \begin{pmatrix} 1 & \frac{w_1}{w_2} & \dots & \frac{w_1}{w_n} \\ \frac{w_2}{w_1} & 1 & \dots & \frac{w_2}{w_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & \dots & 1 \end{pmatrix} \quad (4)$$

where  $a_{ij} = w_i/w_j$  represents the weight of criterion  $i$  over criterion  $j$ . During the aggregating, this eigenvector is always an argument in the AHP process [22]. This argument is associated with a consistency issue, in which the weight values are dependent on the closeness of the eigenvalue towards the perfect consistency. Consistency Ratio (CR) and Consistency Index (CI) were introduced to counter this controversy:

$$CR = \frac{CI}{RCI} \quad (5)$$

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (6)$$

where  $RCI$  is the Random Consistency Index derived from a sample size of 500 randomly produced reciprocal matrices,  $\lambda_{max}$  is the maximum eigenvalue of the judgment matrix, and  $n$  is the number of criteria in the decision matrix.

AHP improves the understanding of a problem by building a hierarchy, which involves the connection of factors and sub-criteria to achieve the decision goal [24]. The selection of a suitable location is based on the study analysis using GIS. This part produces a conceptual suitability index. The selected suitable locations are analyzed to provide a regional suitability

index in the form of a statement generated from the assessment of site suitability using ArcGIS spatial analysis tools. This local indexing can improve the government's policy on ocean renewable energy and increase the effort to produce technology that benefits Malaysia's seas. All generated maps and site suitability analyses were performed using ArcMap software version 10.3.

### III. RESULTS AND DISCUSSION

This section provides the validation of satellite altimeter data with in-situ observation to evaluate their accuracy. The analysis of factors that hindered the ORE development is explained briefly by providing results based on the AHP assessment that is integrated into the GIS environment. The local site suitability index is generated to indicate suitable locations that may have the potential to harness energy.

#### A. Validation of Satellite Altimeter Data

Generally, in-situ measurements such as buoys have always been a benchmark to confirm measurements from space observations and a proven technique to assess satellite altimeters [11]. Figure 2 shows a comparison graph of significant wave height measurements from the satellite altimeters with buoy observation.

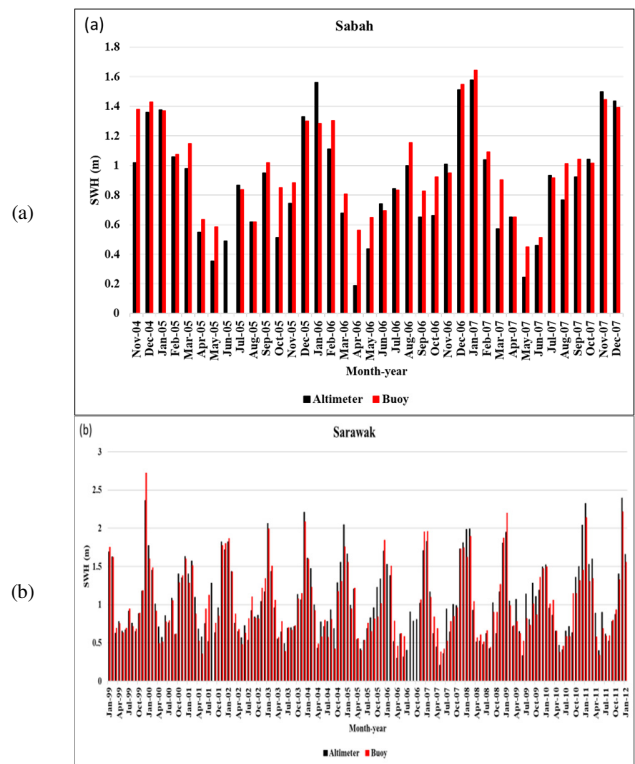


Fig. 2. Trend graphs for wind speed from satellite altimeter compared to buoys for (a) Sabah and (b) Sarawak.

The graphs indicate that the observations of the altimeter  $H_s$  are approximately equal to the buoy measurements. However, the monthly average values of the significant wave height from the altimeter of the Sabah buoy station underestimate the buoy measurements from December 2006 to March 2007. There are

missing observation data for the Sabah and Sarawak buoys from June 2005 and July 2006 to October 2006, respectively. These missing data were excluded in the correlation analysis to avoid degradation of the altimeter performance analysis. Figure 3 presents the scatter plot of the altimeter significant wave height against the buoy data. The correlation value agrees well with previous studies, such as [25-26], stating that satellite altimeter measurements for  $H_s$  are robust and widely accepted to be in close agreement with buoy measurements.

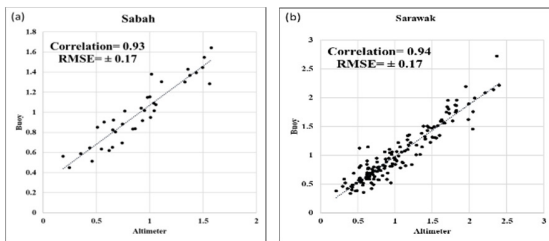


Fig. 3. Correlation graph for significant wave height altimeter and buoy measurements.

**B. Theoretical Resource of Wave Energy**

Figure 4 demonstrates that available wave energy is located at the offshore region of Sabah and Sarawak waters, ranging from 2.84 to 4.21 kW/m. This outcome is similar to the findings of [5]. In Peninsular Malaysia, most of the available wave energy ranges between 1.28 to 1.91 kW/m and 1.93 to 2.77 kW/m, located on the east coast facing the South China Sea.

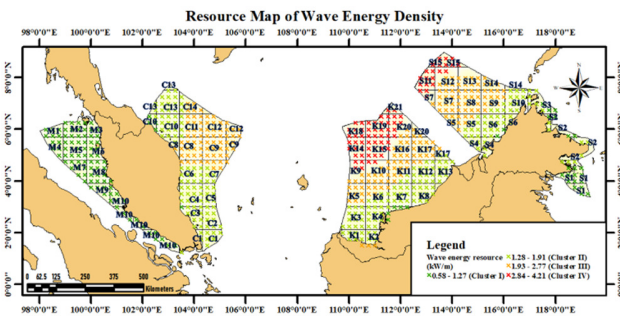


Fig. 4. Theoretical resource map for wave energy of Malaysian seas.

For Peninsular Malaysia, only Terengganu waters are available for wave energy density ranges from 1.93 to 2.77 kW/m. Kapas Island, Terengganu (5.94 km from the Marang shoreline) has an average available wave energy of 1.91 kW/m. Besides that, Tenggol Island, Terengganu (28.72 kilometers from Kuala Dungun) is also indicated with an average wave energy of 1.94 kW/m.

**C. Restriction Map**

In developing countries, marine space exploration is vital for economic growth, fostering activities, such as aquaculture, fisheries, ecotourism, and deep-sea resource exploration. Simultaneously, it offers valuable renewable energy resources for future electricity generation. As marine space use increases, ocean renewable energy development must avoid conflicts for sustainable and low-risk environmental impacts [27]. Based on

Figure 5, most of the activities operate on the east coast of Peninsular Malaysia and the north coast of Sabah and Sarawak, facing the South China Sea. Malacca Strait is important for Malaysia as it provides a route for global trade, which shortens the sea route between the Indian and the Pacific Oceans. Each criterion was buffered using the geoprocessing buffer tool of ArcGIS 10.3. Model Builder tools were applied by constructing workflows that sequentially arrange the geoprocessing tools, namely the Buffer, Feature to Raster, Is Null, and Raster Calculator tools, to generate the restriction map. The Raster Calculator was employed to create and execute the criteria layers to generate the restriction map. Figure 6 shows the criteria buffer map within the Malaysian EEZ.

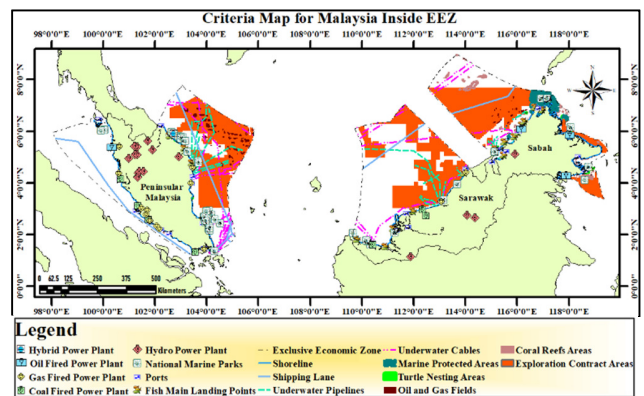


Fig. 5. Mapping of the considered criteria inside the EEZ.

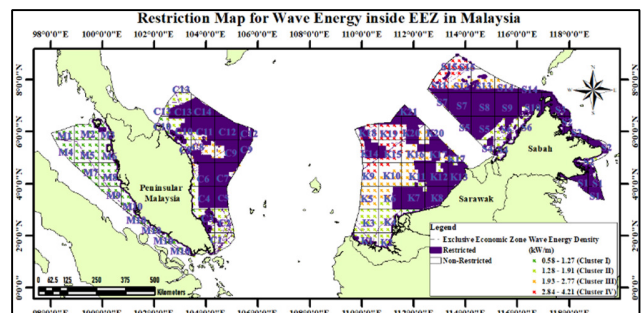


Fig. 6. Restricted and non-restricted zones from the buffer analysis.

The highest potential for wave energy within the range of 2.84 to 4.21 kW/m is offshore Sarawak and Sabah. Meanwhile, in Terengganu waters, most of the location has available wave energy within the range of 1.93 to 2.77 kW/m.

**D. Integration of AHP with GIS for Site Suitability Analysis**

The construction of a hierarchical tree, which involves criteria, sub-criteria, and alternatives, is the primary step of the AHP process [28]. The weightage value for the criteria is generated by averaging the comparison value of each criterion. To get the average value, the comparison matrix is then normalized by dividing the corresponding matrix value in column order with the sum of cell values in the same column. CR (5) was used to evaluate the weight consistency. According to [29], if the CR is greater than 10% or 0.10, the judgments of the criteria based on the pairwise comparison indicate inconsistency, and therefore a reanalysis of the judgment must



be performed. Table III demonstrates that CR is 0.045 or 4.5%, which is below the limit value of 0.1. Thus, the comparison of the criteria utilized for this study was validated and accepted. Table IV displays the weight values of the considered criteria. These weight values were then applied in the Weighted Sum Tool to generate the indexed suitability map.

TABLE III. CONSISTENCY RATIO FOR THE COMPARISON MATRIX

CI	RCI (n=11)	CR	Percentage
0.068	1.510	0.045	4.5%

TABLE IV. CRITERIA WEIGHT VALUES GENERATED FROM AHP

Criteria	Weightage
Port	0.024
Shoreline	0.043
Oil and gas field	0.138
Fish main landing point	0.021
Underwater cables	0.151
Underwater pipelines	0.151
National marine parks	0.065
Marine protected areas	0.065
Shipping lane	0.212
Coral reefs	0.065
Sea turtle nesting	0.065
<b>Sum of columns</b>	<b>1</b>

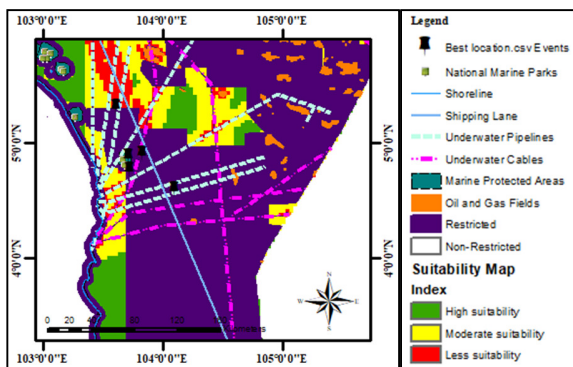


Fig. 7. The area proposed in [31] (indicated by the black pinpoint) and embedded into the suitability map generated by this study. The best location falls within the restricted area.

The deployment of Wave Energy Converters (WECs) depends not only on available resources, wave characteristics, and depth, but also on a detailed site assessment [30]. In [31], it was determined that Terengganu and Sarawak waters were the most suitable areas to deploy WECs. The selection was based on available wave resources, depth analysis, and hot-spot area analysis. Figure 7 portrays the five best locations in Terengganu waters that were integrated into the suitability map generated in this study. The analysis reveals that the locations proposed in [31] are in restricted areas for energy development, making them less suitable for WEC deployment. This study provides a more thorough analysis to identify suitable sites for wave renewable energy development compared to previous research. Based on the site suitability analysis for wave energy resources, Figure 8 shows the most suitable locations with high wave energy resources identified in Sarawak offshore areas (zones K9, K10, K15, K18, and K19). Among them, the K18

zone has the highest wave resource with an average of 3.99 kW/m and wave height in the range of 3.82 to 4.21 m.

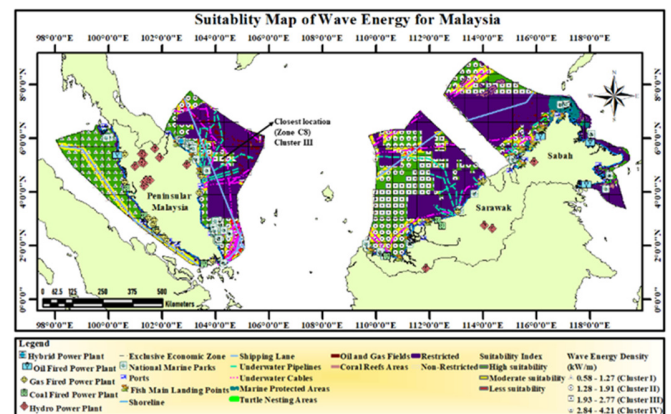


Fig. 8. Suitability map of wave energy resource for Malaysia

TABLE V. HIGH SUITABILITY AREA FOR WAVE ENERGY IN MALAYSIA'S EEZ

Location	Zone	Nearby conflicts
Terengganu	C8 (offshore)	Exploration contract areas Underwater cables Underwater pipelines Shipping lane
Sarawak	K9, K10, K11, K16, K18, K19 (offshore)	Exploration contract areas Underwater cables Underwater pipelines Shipping lane
Sabah	S11, S12, S13, S14, S15 (offshore)	Exploration contract areas Underwater cables Coral reefs

#### IV. CONCLUSION

This study significantly contributes to the exploration of Malaysia's wave energy potential, utilizing multimission satellite altimetry and the AHP for site suitability analysis. A comprehensive approach was adopted, leveraging extensive significant wave height data from various altimetry missions to address the challenges posed by the lack of in-situ data in Malaysia's ocean renewable energy development. The study showed that satellite altimeter data contribute to the accurate measurement of significant wave heights, having a good correlation coefficient and RMSE value. Additional analysis, using multi-criteria decision-making from the AHP approach to generate the criteria weight for further suitability analysis, revealed a good consistency ratio of 0.045, which is less than 0.1. This result indicates that the criteria judgment is good and acceptable to be used in the Weighted Sum tool of ArcGIS to generate the suitability map. Seven zones (K9, K10, K15, K18, K19, S11, and S15) were identified as highly suitable locations with high wave resources (2.84-4.21 kW/m). The outcomes of these suitability analyses generated a local conceptual suitability index, which is a useful evaluation indicator in site selection analysis. The combination of satellite altimetry, AHP, and GIS presents a comprehensive and tailored approach to overcome the specific challenges, particularly in the feasibility study of wave energy and the selection of suitable locations. This study also offers valuable information for stakeholders

and the government in advancing the development of wave energy as an alternative source of electricity.

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